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N° 6905

April 2009

Thème NUM

ISSN 0249-6399 ISRN INRIA/RR--6905--FR+ENG

INSTITUT NATIONAL
DE RECHERCHE
EN INFORMATIQUE
ET EN AUTOMATIQUE

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Thème NUM — Systèmes numériques
Équipe-Projet MESCAL

Rapport de recherche n° 6905 — April 2009 — 16 pages

Abstract: In this document, we propose a component-based approach to provide a well-suited solution to the programming and deployment problems of systems on chip (SoC) that can become increasingly complex and heterogeneous. Focusing on the aspect of observation, we show, from system to application, that components help in observing all software levels. We present the EMBera prototype and relate our experience in implementing it on two different platforms: a Linux-based 16-core SMP machine and a 5-core embedded system developed by STMicroelectronics.

Key-words: MPSoC, observation, component

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Vers une observation de systèmes multiprocesseur sur puce basée sur des composants

Résumé : Dans ce rapport technique, nous proposons une nouvelle approche à base de composants qui constitue une solution adaptée aux problèmes de programmation et de déploiement de systèmes et d'applications sur puce (SoC). Ces problèmes sont particulièrement difficiles à appréhender sur des architectures hétérogènes. Nous nous intéressons plus précisément à l'observation de ces applications, depuis le niveau système jusqu'au niveau de l'application elle même. Nous présenterons le prototype logiciel EMBera ainsi que ses portages sur deux plates-formes multi-processeurs/multi-coeurs: Une première plate-forme embarquée à 5 coeurs développée par STMicroelectronics et une seconde plate-forme SMP à base de 16 coeurs AMD/Opteron. Le document se termine par une série d'expérimentations et d'évaluations.

Mots-clés : Systèmes multiprocessur sur puce, observation, composant

1 Introduction

Since manufacturers have to integrate new hardware technologies, to develop new system software and to provide new sophisticated functions in a very short time in order to market. Consequently, the design of multi-processor system-on-chip (MPSoC) is a notoriously complex issue[1].

A typical MPSoC commercialization involves the porting of system software to the new architecture, the production of dedicated development tools and the platform-specific implementation of MPSoC applications. This platform-dedicated process is however not adapted to future MPSoC which follow current trends in processor development and will integrate dozens and even hundreds of computing cores in various hardware architectures.

To face the challenge of parallel multi-core architectures, the MPSoC needs new programming models and development tools. Ensuring rapid software development, as well as provide easy and efficient tuning will be mandatory to target architectures. As software development involves debugging and software tuning involves performance evaluation, both need adapted solutions for MPSoC observation.

We are particularly interested in MPSoC observation. It consists in obtaining meaningful information about the execution of embedded applications. Current techniques for observing MPSoC are based on gathering execution traces mostly from hardware and operating system. Because these solutions are closely related to the underlying platform, they offer a poor extensibility to new architectures and programming strategies. In order to overcome the lack of extensibility, we propose to utilize software components: a proven solution for reusing and organizing application code [2].

Indeed, software components are largely used in the software engineering domain and have also been accepted in the distributed systems area [3][4], including MPSoC application development [5]. Besides, components enable the isolation of low-level system concerns from application level issues. This separation of concerns may be used for observation of the application in a more comprehensive way.

In this document, we investigate the use of components for observing MPSoC applications. We propose a component model for application and show that it can be used for multi-level observation. We relate our experience in implementing this model on two different platforms, discuss the problems of implementation as well as what the basic observation functions of a system should be.

We will first present the related work on observing embedded and parallel platforms, and then we will introduce EMBera which is our proposition for observing MPSoC using components. Finally, we will describe our experiences in implementing EMBera model on two different platforms as well as the observation performed on each implementation.

2 Related Work

The observation of applications is a problem which has been already addressed by domains such as embedded, parallel (high performance computing) and software component systems. On the one hand, MPSoC and parallel observation approaches give us the current practices on gathering information of multiprocessor applications, dealing with embedded systems constraints and with parallel execution issues. On the other hand, components give us a high level of abstraction from the target system. This section aims at briefly presenting the work carried out in each domain.

The historically concurrent development of SoCs' software and hardware has resulted in the production of software that is specific to the underlying hardware. Indeed, SoC software is usually low-level (drivers, operating systems) and in charge of the management of a proprietary hardware. As a consequence, the tools developed for SoC platform observation are also proprietary and low-level. They mostly give information about hardware state (memory dumps, CPU register values) and kernel events (interruptions, function calls). They usually do not provide information about the application layer and even if they do, there is no mapping between application operations and lower-level observation data. Examples of typical SoC observation tools are KPTrace [6] and OS21 Activity Viewer, both developed by STMicroelectronics. The first tool operates on a Linux based system [7] while the latter works for OS21, an in-house real-time operating system. Another example is the SpyKer product [8] proposed by LinuxWorks.

As the MPSoC becomes *de facto* parallel systems, we cannot ignore observation solutions existing in the domain of parallel architectures. There are, indeed, proven tools for observing threads in the shared-memory parallel systems. We can cite Gthreads [9] or the POSIX Thread Trace Toolkit [10]. In the same time, there are tools [11, 12] for monitoring distributed-memory parallel applications written in MPI [13] or OpenMP [14]. However, as the MPSoC is not likely to become dedicated to a given parallel programming model, these tools cannot be applied "as is".

A different approach to observation is proposed in component-based software systems. Unlike SoC systems, observation is mostly focused on high-level software layers like end-user applications and component-oriented middleware. It typically covers component architecture and component interaction. The Fractal component model [2], for example, can detail the set of executing components and the existing bindings between components. It can also trace component creations and communications. Similarly, OpenCCM [15], an open-source implementation of the CORBA Component Model [4], uses interceptors in order to capture method invocation, and thus, monitor component creations and communications. The same approach is applied to the implementations of the EJB model [3]. Component observation at the application level has an important advantage which is to be independent of the underlying system software and hardware. However, it is unfortunately unrelated to low-level performance metrics which are crucial for embedded system development.

A possible solution to bridge the gap between components and MPSoC is to use component-based operating systems, but some problems remain with the existing implementations. For example, Pebble [16] and Flux OSKit[17] do not target embedded systems. The PURE project [18] does target deeply-embedded systems but focuses mainly on the trade-off between efficiency and software engineering and not on observation. The only project applying components to MPSoC we are aware of is the Nomadik Multiprocessing Framework project [5] of STMicroelectronics in which our work is to be integrated.

3 The EMBera Observation Model

The major motivation behind EMBera is to provide an observation solution for embedded systems so that:

- it can be used to observe different types of embedded applications (i.e. application-independent).

- it can be used to observe different levels related to the execution of an embedded application.
- it can be used on different MPSoC hardware platforms (i.e. platform-independent).
- it can be configured to serve a specific observation context.

In other terms, our main objective in this section is to be able to study about observation in generic terms and yet be able to efficiently observe specific embedded hardware and software. We will focus on the way to define observation functions separately from the embedded platform. Then, we will use components as they appear to be a successful solution to the problem of separation of concerns.

The EMBera model is inspired by the Fractal component model [2]. We have chosen Fractal since it is a general component model that is system and language independent. Indeed, it can be used at the system level, as well as middleware or application level and it can be implemented in Java, C or other programming languages. Another major advantage of Fractal is that it is already used at STMicroelectronics which defines our working context.

3.1 The EMBera Component Model

An EMBera application is composed of a number of interconnected components. A component is a software entity with a well-defined functionality. A part of this functionality can be visible to other components, in this case the component defines *provided* interfaces. Some components may depend on this functionality, in that case they define *required* interfaces. *Connections* between components are established by linking required and provided interfaces.

The components in EMBera are active entities and each component has its own execution flow. This choice follows the current practice for MPSoC applications in which multiple treatments are executed on different processor units.

EMBera components provide a predefined interface for component control. The control operations include component creation, component interconnection and component life-cycle management (launching and termination).

3.2 The Motion-JPEG Decoder Application Example

To illustrate the EMBera model, let us consider an existing application for decoding a stream of independent and individually encoded JPEG images[1].

The decoding process is done by dividing each individual image in smaller blocks. Each block is decoded mainly by applying a Huffman algorithm, a pixel reordering and the Inverse Discrete Cosine Transformation (IDCT). Then, all the blocks are reordered in order to reconstitute original images.

For computing independent data in parallel, the MJPEG decoder code can be divided into three parts. We intend to set each part to one EMBera component. One Fetch component deals with file management, Huffman decoding and pixel reordering, one or several IDCT components computes IDCT, and one Reorder component reassembles images and eventually sends data to an output display. Figure 1, presents the MJPEG resulting application. The connections between components describe the treatment flow of image data.

[1] Implemented for [19] in the scope of the cycle-accurate simulation platform.

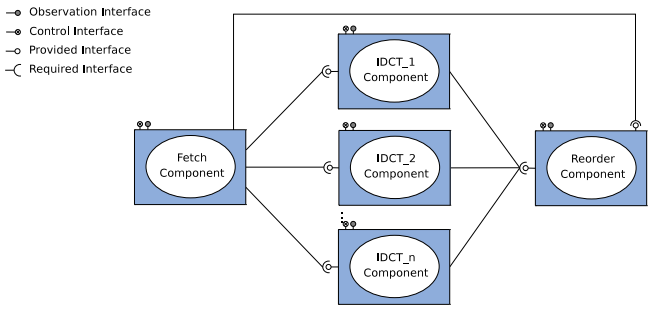


Figure 1: Componentized MJPEG Decoder Application

3.3 Observation in EMBera

We have decided to explicitly model the observation in EMBera. For this purpose, we have defined a new control interface dedicated to observation, that we have called *observation interface*. This interface provides a set of observation functions.

We consider that MPSoC observation has to take into account at least three levels: the system, the middleware and the application level. The observation interface may provide functions related to each level such as memory and system time, communication time, and application structure (e.g. the component structure). However, the exact information to be provided by this interface is still to be defined.

The information obtained, accessible through the observation interface, is gathered and analyzed by a new component connected to the observation interfaces. We have named it the *observer component*.

4 Implementation of EMBera on SMP - Linux

We have implemented EMBera on two different platforms: a 16-core SMP Linux system and a 5-Processor STMicroelectronics MPSoC. The former platform is a standard x86 multiprocessor architecture, the latter is an MPSoC platform currently used in STMicroelectronics products. In the current and in the following sections, we will discuss the implementation details of EMBera, the MJPEG application introduced on 3.2 and the observation carried out on each platform.

The 16-core platform is a Symmetric Multiprocessor eight dual core AMD Opteron 2.2 GHz and 2 MB of cache memory for each processor. It is organized in eight nodes and has in total 32 GB of main memory (4 GB of local memory). Each node has three connections to communicate with other nodes. This platform uses a Linux kernel 2.6, providing native C compilation and POSIX thread support [20].

This platform follows a NUMA (Non-Uniform Memory Access) memory organization. A NUMA platform is a multiprocessor system in which the processing elements are served by multiple memory levels, physically distributed through the platform. Such distributed memory is seen by the application as a single shared memory [21]. However, the access time to the distributed memory changes depending on the distance between the processor and the memory.

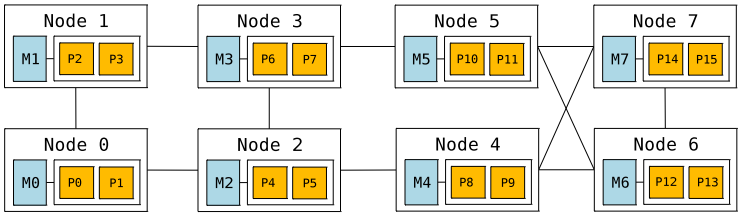


Figure 2: 16-core Symmetric Multiprocessor Platform.

4.1 EMBera Model

The implementation of EMBera is done in the C language. Current compilers for STMicroelectronics processors support C, C++ and Java languages. However, the C language is the *de facto* standard for embedded software due to its performance and for legacy reasons [22].

An EMBera application is a Linux user process. A component is a data structure and a POSIX thread. This thread belongs to the Linux user process and provides an execution support for the code inside the component.

The communication between components is carried out by a simple one way asynchronous message-oriented mechanism, through an established connection. The mechanism implements `send` and `receive` primitives. A *provided interface* receives messages while a *required interface* sends those messages. It is also implemented as a FIFO data structure, we have named *mailbox*. A *required interface* corresponds to a pointer towards a provided interface (mailbox). A *connection* is established by setting the pointer on the required interface to a specific provided interface.

The deployment of any EMBera application is carried out by explicitly invoking control functions into the `main` application function.

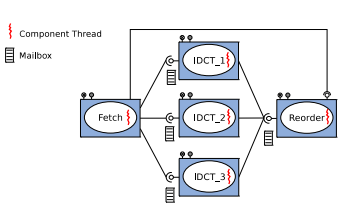
4.2 Observation

The observation interface is implemented as a couple of interfaces (one provided and one required) and a set of observation functions.

This couple of interfaces for the observation is created by default on any EMBera component. Both interfaces are able to receive messages requesting observation information (using the provided interface) and return the requested information (using the required interface).

The set of observation functions concerns functions for collecting execution data from different software levels involved in the execution of the application. The current implementation addresses three levels of observation: the operating system, the middleware, and the application itself. The operating system is the Linux system software which directly manages the SMP platform. Most of the information related to the platform and resources utilization can be retrieved or inferred from this level. The middleware concerns the EMBera communication primitives, the application level being the component structure and the code inside EMBera components.

The observation information provided is obtained by implementing the observation functions into the EMBera component implementation without modifying the application code. We will now describe the functions currently implemented for observing each level.



(a) Component Architecture

```
component *fetch = createComponent (10, "fetch", fetch_function);
interface *fetchReorder = createInterface(fetch, "fetchReorder", "client");
interface *fetchIDCT1 = createInterface(fetch, "fetchIDCT1,  "client");
...
component *idct1 = createComponent(20, "idct1", idct_function);
interface *_fetchIdct1 = createInterface(idct1, "_fetchIdct1", "server");
interface *idct1Reorder = createInterface(idct1, "idct0Reorder", "client");
...
component *reorder = createComponent (30, "reorder", reorder_function);
interface *_fetchReorder = createInterface (reorder, "_fetchReorder", "server");
interface *_idctReorder = createInterface (reorder, "_idctReorder", "server");

componentConnect (fetch, fetchReorder, reorder, _fetchReorder);
componentConnect (fetch, fetchIDCT1, idct1, _fetchIDCT1);
...
componentConnect (idct1, idct1Reorder, reorder, _idctReorder);
...
```

(b) Deployment Program

Figure 3: EMBera MJPEG Architecture and Deployment

Operating System: We have currently gathered information about the execution time and the memory occupation. For obtaining the execution time, we have calculated the time elapsed between the starting of a component and the termination of its code execution. The time has been measured by using the `getTimeOfDay` system function. For obtaining the component memory, we have calculated the memory allocated for the component thread and the size of memory allocated for all the component provided interfaces and related structures. These measures have been gathered by using `pthread_attr_getstacksize` and `sizeof` functions respectively.

Middleware: We have obtained information about the execution time of `send` and the `receive` operations by instrumenting `send` and `receive` primitives. The time stamping is also supported by the `getTimeOfDay` system function.

Application: The information we have collected is about the component structure and the total number of communication operations performed. The former consists in listing provided and required interfaces of the component, while the latter is achieved by adding counters to `send` and `receive` primitives and associating them to components.

4.3 The Motion-JPEG Decoder

Figure 3(a) depicts the architecture of the MJPEG EMBera application implemented with five components: one Fetch, three parallel IDCT and one Reorder component. Figure 3(b), shows the `main` application function, in which each one of the five components and its interfaces are instantiated. Then, this function specifies the connections between all the components.

The MJPEG application is executed on two different input files containing 578 and 3000 JPEG images respectively. The dimensions of each single image are the same in both cases. These different input sizes ensure the observation of the different behaviors for each component during execution.

4.4 Observation of the Motion-JPEG Decoder

To illustrate the EMBera observation model, we have observed the execution of the MJPEG application by using the observation interface and the implemented observation functions.

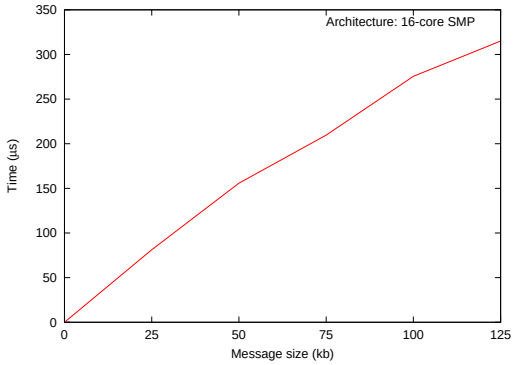


Figure 4: Send Primitives Execution Time.

Operating System: The data on table 1 corresponds to the component execution times and the component memory initially allocated.

Component	Time_{578} (μs)	Time_{3000} (μs)	Mem (kB)
Fetch	4 084	20 088	8 392
IDCTx	4 084	20 218	10 850
Reorder	4 086	21 538	13 308

Table 1: MJPEG Components Execution Time and Memory Allocated

What we observe in both execution cases is the fact of having three IDCT components computing in parallel balances the execution times of the three parts of MJPEG application.

For this experience, the memory values obtained for Linux thread stack correspond to 8 392 kb. The memory allocated to the Fetch component memory corresponds to this value, therefore, the component does not instantiate any provided interface. Higher memory values for IDCTs and Reorder represent their provided interfaces.

Communication: Figure 4 presents the evolution of `send` execution time when the message size increases. The execution time values obtained shows that the time spent for sending a message increases almost linearly with the size of the message.

The particular interest of increasing the message sizes is to observe the behavior of EMBera communication primitives, executed on different platforms. Based on the linear behavior of the figure, we can deduce that the time of executing a `send` operation mainly depends on the size of the message on a SMP platform.

Application: One first information obtained deals with the number of communication operations performed (table 2).

The values in this table indicate that Fetch component sends messages but it does not execute any `receive` operation. The IDCT components receive and send the same amount of messages, and the Reorder component receives the same amount of messages initially delivered by Fetch. If we do not have access to internal code of components, this information will be useful to infer the functioning of the application: the Fetch component takes an input file, divides it on a set messages and sends the third

Component	$send_{578}$	$receive_{578}$	$send_{3000}$	$receive_{3000}$
Fetch	10 386	0	53 982	0
IDCTx	3 462	3 462	17 994	17 994
Reorder	0	10 386	0	53 982

Table 2: MJPEG Components Communication Operations Performed

part of this set to each IDCT; each one of them executes its code on the received message and delivers to the Reorder component only one message per received message; the Reorder component receives all results from the three IDCTs.

```
Interfaces component [IDCT_1]
------------------------------
[Interface]     [Type]
introspection   provided
_fetchIdct1     provided
introspection   required
idctReorder     required
```

Figure 5: Interfaces for Component IDCT_1

Another information obtained is related to component structure. Figure 5 shows that IDCT1 component has four interfaces: the two observation interfaces (one provided and one required), the provided interface for the Fetch component and the required interface to connect to the Reorder component. This observation can provide valuable information for applications which configuration changes dynamically.

The information obtained by observing the MJPEG application through the observation interface ensures a better understanding of the application behavior and therefore helps to find potential performance improvements. For example, the execution times indicate that the application is well load-balanced for the JPEG input size but if that size changes, the execution times could cause a bottleneck on the IDCT components.

5 Implementation of EMBera on MPSoC - OS21

The STi7200 MPSoC platform in figure 6 is composed by one 450 Mhz general purpose RISC ST40 CPU and four 400 Mhz accelerators ST231 CPUs. The ST40 CPU has access to the total on-chip memory including one big external block of 2 GB SDRAM memory. Each ST231 CPU has access to a block of local data and control memory.

The ST231 and ST40 CPUs communicate by using one shared block of memory associated with one interruption controller. The chip can be programmed by using STMicroelectronics implementation of standard ANSI C. It is supplied with a complete toolset including optimized C-compilers, assemblers, linkers, debuggers, an IDE, a code profiler and a set of observation tools. As ST40 and ST231 processors have different instruction sets, each has its own toolset.

STi7200 processors run OS21: a lightweight, real-time multitasking operating system (RTOS). The OS21 RTOS provides portable APIs to handle tasks, memory, interrupts, exceptions, synchronization, and time management. The OS21 tasks behave like

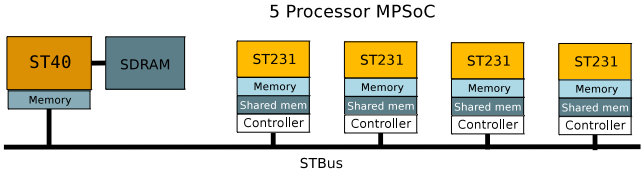


Figure 6: STi7200 Platform

processes and communicate via a specific middleware developed by STMicroelectronics - EMBX. This middleware manages shared memory regions accessible by several or by all the CPUs. These memory regions are called distributed objects and are accessed by dedicated `EMBX_Send` and `EMBX_Receive` functions. The `EMBX_Send` is an asynchronous operation corresponding to a write operation on the distributed object. The `EMBX_Receive` is a synchronous operation corresponding to a read operation on the distributed object.

5.1 EMBera Model

An EMBera application is a set of OS21 tasks, each task representing a component. The current implementation supports one component per CPU and thus avoids dealing with the low-level multi-tasking OS21 support.

The component *provided interface* is represented by a distributed object. The component *required interface* corresponds to pointers towards a distributed object. A *connection* between both interfaces is established using EMBX primitives to manage distributed objects.

When a component needs to communicate through a required interface, it executes `EMBX_Send` and thus updates the corresponding distributed object. As the distributed object represents a provided interface, the component providing interface needs to execute `EMBX_Receive` in order to end the communication.

The deployment of an EMBera application on the STi7200 platform consists in loading one binary code per CPU which is performed by using STMicroelectronics proprietary devices and software tools. Each binary code contains a `main` function which creates, connects, starts and stops the component.

5.2 Observation

As shown in the Linux EMBera implementation, the observation is applied to three software levels: the Real Time Operating System (RTOS), the middleware and the user application. We will discuss the observation at the RTOS level and at the middleware level since the user application level observation is identical to the Linux implementation.

Operating System: At the system level, our objective is to observe the system memory utilization and the component task execution time. When the OS21 initializes, the component task is created and starts . We can observe the task execution time by using an OS21 supplied system function, the `task_time`.

The system memory used by an EMBera component implementation is related to the local memory for the task and the SDRAM memory for the distributed objects. The

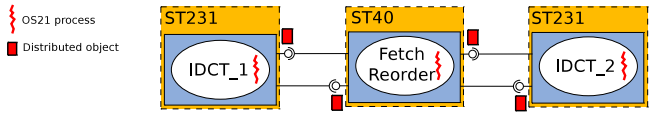


Figure 7: Componentized MJPEG Decoder Application on STi7200 platform

observation of the local memory is carried out by OS21 functions. Those functions provide the tasks memory size and the amount of memory currently used which, in the SDRAM, is equal to the size of all distributed objects. This size value is fixed and gathered at component creation time.

Middleware: At the middleware level the observation mechanism is the same as in the Linux implementation and is based on gathering execution information about the sending and the reception of messages. What differs is that the time stamp is given with the `time_now` OS21 system function. This function gives the local time on each CPU.

5.3 The Motion-JPEG Decoder

Out of the five processors, we will use three (ST40 and two ST231) on the STi7200 platform for executing the MJPEG application. Indeed, the software toolset provided by STMicroelectronics for our experience supports only three processors.

Figure 7 presents the componentized MJPEG application, deployed on the STi7200 platform. We have decided to create a single I/O component by merging the Fetch and the Reorder functionalities in a Fetch-Reorder component. This component is deployed on the general purpose ST40 CPU. It is connected with the two IDCT computation components, each one deployed on one ST231 CPU.

5.4 Observation

We will now show and discuss the observation information provided at RTOS level and EMBera middleware level. The information collected at the application level for the OS21 MJPEG implementation does not provide additional information in comparison with the Linux implementation.

RTOS: In table 3, we show the overall execution time of the components tasks and the local memory consumption. On the Linux EMBera implementation, the Fetch and the Reorder components computation time is almost the same as the IDCTx components. On the OS21 implementation, the Fetch-Reorder component runs ten times slower than IDCTx components. This difference might be due to the ST40 processor which is general purpose and computes slowly the Reorder algorithm.

Component	Time (s)	Mem (kb)
Fetch-Reorder	1173	110
IDCTx	95	85

Table 3: MJPEG Components Execution Time and Memory Allocated

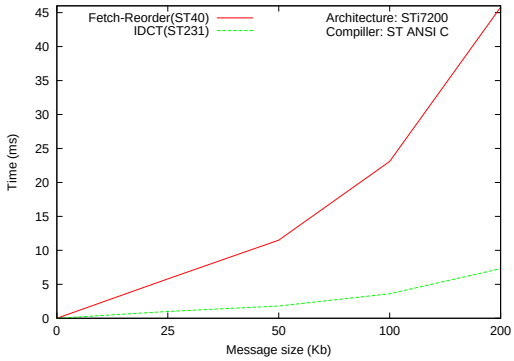


Figure 8: EMBera send execution time over 578 MJPEG images

It is interesting to observe the huge difference between the Linux IDCT component overall execution time ($\tilde{4}$ s) and the OS21 IDCT component overall execution time($\tilde{1}$00 s). Despite the frequency differences between the SMP platform processors and the STi7200 accelerators, the execution time difference is not justified. This problem might occur because we execute the Linux version of the MJPEG code without applying any optimizations.

The 85 kB memory consumption on the IDCT component corresponds to 60 kB for the task data and component structure and 25 kB for one distributed object. The Fetch-Reorder component uses two distributed objects which justifies the 100 kB consumed memory.

The 85kB allocated memory for the IDCT component is several times smaller than the memory allocated for the Linux IDCT component (8 MB) but corresponds to the architectures memory difference (1 MB for MPSoC and 32 GB for Linux).

Middleware: In figure 8, we show the average execution time of the EMBera send function for 578 MJPEG images, performed by the Fetch-Reorder component and the IDCT component. We can see, in figure 8, that IDCT component executes the send operation faster than the Fetch-Reorder component for the same message size. That difference in the execution time is due to the hardware architecture of the STi7200 platform, which favors the ST231 accelerators in memory operations. These memory operations are the most time consuming. Indeed, the general purpose ST40 CPU is mainly designed to access peripherals while ST231 accelerators are designed for intensive computing which needs fast memory access.

The message size has a direct consequence on the application performance. Indeed, the performance of the EMBera send function is linear for message sizes smaller than 50 kB. Over 50kB, the send function decreases its performance. Since the performance depends on the size of the message, we can deduce from this observation that OS21 EMBera implementation is well suited for the hardware architecture when the message size is less than 50 kB.

The generic observation information we gathered in this example can be useful for optimizing the communication time between the components. For instance, we can force the Fetch-Dispatch component to send different number of messages, according to the message size, in order to balance the EMBera send execution time between the components.

6 Conclusions and Perspectives

In this document, we have introduced EMBera, a component-based model for observing MPSoC. We have presented two implementations of EMBera on a SMP and an MPSoC platform. We have implemented a basic video decoding application using EMBera components and have shown how multi-level observation can be carried out.

The EMBera model has enabled us to set an application in terms of components. The observation modeled in EMBera provides us with a generic mechanism for obtaining meaningful information about the execution of an MPSoC application. Both implementations demonstrate that the componentized MJPEG application can be observed without modifying its code. Indeed, we are able to observe the application behavior based on the interaction among the application components as well as between the components and other execution levels.

As a matter of fact, we have found interesting to observe at least three execution levels: the operating system, the middleware and the application. At the OS level, we have proposed to implement functions for observing memory and execution times. At the middleware level, we have observed the behavior of communication primitives. Finally, at the application level we have focused on the observation of the use of middleware and on the component structure. According to us, these functions are the basis to observe any MPSoC application.

In the ongoing work, we focus our research on defining and extending EMBera observation functions, for instance, cache misses and the evolution of memory during the execution of a program. For extending observation capabilities, we are working on abstracting operating system observation functions and communication observation metrics from the component model. We will concentrate our future work on what functions should be provided with the observation interface, how to select the events to be observed, how to set the treatments to apply and finally, how to manage multi-level information.

The current approach for observing is mainly based on collecting summarized information about the execution. However, this information does not give a detailed view of the application behavior. For this reason, we plan to implement an event-trace-support for collecting detailed events.

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INRIA - Domaine de Voluceau - Rocquencourt, BP 105 - 78153 Le Chesnay Cedex (France)
http://www.inria.fr
ISSN 0249-6399